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PROJECT VANGUARD REPORT NO. 18
MINITRACK REPORT NO. 1 - PHASE MEASUREMENT

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**Previous reports of the Project Vanguard
Report series received limited distribution.**

PREFACE

As a part of its effort in the International Geophysical Year (July 1957 through December 1958), the United States will attempt to launch a number of artificial satellites into orbits around the earth. Overall management of the joint Army-Navy-Air Force program is the responsibility of the Office of Naval Research, which has established Project Vanguard at the Naval Research Laboratory to carry out the technical program.

The most basic problem created by an earth satellite after it is placed in its orbit are those associated with proving that the satellite is in fact orbiting, and the measurement of its orbit. The Minitrack system was developed at the Naval Research Laboratory to provide acquisition and tracking of the satellite by radio techniques. A subminiature radio transmitter operating continuously for at least two weeks will be provided within the satellite to illuminate antennas at ground tracking stations. By phase-comparison techniques, these ground stations will measure the angular position of the satellite as it passes through the antenna beam, recording its "signature" automatically without the need for initial tracking information. Analysis of this signature will provide the complete angular history of the satellite passage in the form of direction cosines and time coordinates. These data will be quickly transmitted to a central computing facility for the computation and publication of ephemerides.

This report, the first in a series describing the Minitrack system in detail, discusses the Minitrack system briefly, and provides a detailed description of the phase measurement portion.

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ABSTRACT

The "Minitrack" system for tracking an artificial earth satellite, which has been developed as a part of Project Vanguard, is described briefly, and the phase measurement portion of this system is described in detail. The actual measurements performed by Minitrack are phase comparisons of signals resulting from the illumination of the ground station antenna field by the satellite transmitter. Eight antennas arranged in five pairs along two orthogonal baselines feed rf receivers which convert rf signals to the af signals used in the actual phase comparisons. The phase measurement equipment is designed to perform the desired phase comparisons and provide analog records of all five phase comparisons with an error of less than 1 percent, and to provide digital records of the two "fine" channels with an error of less than 0.1 percent, corresponding to a space angle error of 4 seconds.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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PROJECT VANGUARD REPORT NO.

MINITRACK REPORT NO. 1: PHASE MEASUREMENT

INTRODUCTION

"Minitrack," a radio system for tracking an earth satellite, has been developed at the Naval Research Laboratory as a part of Project Vanguard. The general aspects of this system have been discussed elsewhere.* Briefly, it is a radio phase-comparison system employing a low-power, lightweight transmitter in the satellite to illuminate a total of eight antennas arranged in five pairs along two orthogonal baselines as shown in Fig. 1. From the five phase comparisons made with these antenna pairs, two direction cosines of the line connecting the center of the antenna system and the satellite are determined as a function of time as the satellite passes through the pattern of the receiving antennas. The five phase comparisons made to determine the two direction cosines are: north-south fine, north-south medium, north-south coarse, east-west fine, and east-west medium. The actual measurements are made from the fine baselines; the medium and coarse baselines are used for ambiguity resolution.

A block diagram of the overall Minitrack ground station is given in Fig. 2. This report describes that portion of the ground station from the outputs of the rf receivers to the final records of the tracking data. The functions performed by this equipment are the following:

1. To provide the system with the desired narrow post-detection bandwidth,
2. To perform the basic phase comparisons in a manner compatible with the accuracy needed in each case, and
3. To record the data in such a manner that the time and angle can be read quickly to the necessary accuracy.

These functions are performed in a number of chassis contained in three equipment racks: one for the measurement equipment and two for the recorders. The data system is shown by the solid blocks in the block diagram of Fig. 3, while the dotted blocks show the various components of the time standard unit. The time standard will be described completely in a forthcoming report and is shown here only to indicate the tie-in of the data and time systems. As far as the data measurements are concerned, it suffices to say that the basic separation frequency (500 cps) furnished to the receiver system by the time standard is derived by counting down from the basic time standard oscillator, and that the 500-cps reference from the receiver system is counted down, compared with and adjusted to match the output of the time standard. The positive zero crossing of the reference signal controls the start of the reading time in the digital phase meter. The net result is that the starting time of any digital data reading is known to within $100 \mu\text{sec}$ with respect to the time standard. The time standard is in turn maintained within $\pm 0.5 \text{ msec}$ with respect to National Bureau of Standards radio station WWV.

*Mengel, J. T., "Tracking the Earth Satellite, and Data Transmission, by Radio," Proc. I.R.E. 44(No. 6):755-760, June 1956

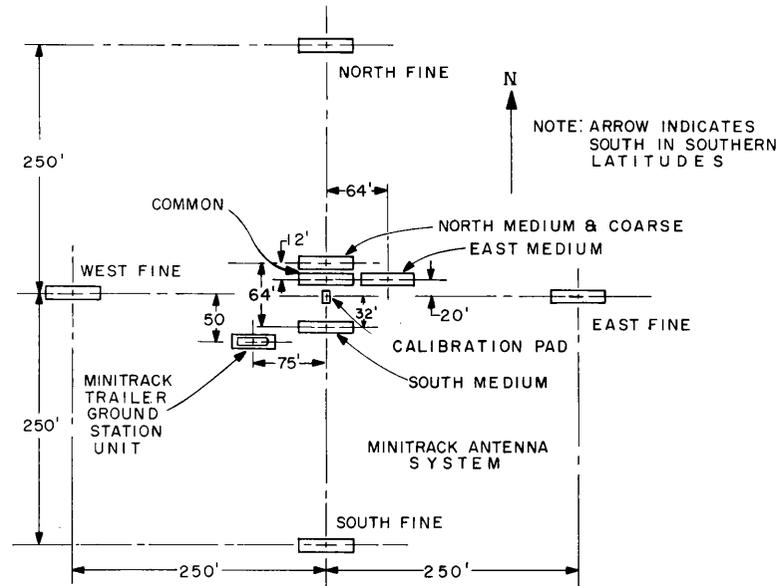


Fig. 1 - Minitrack antenna field layout

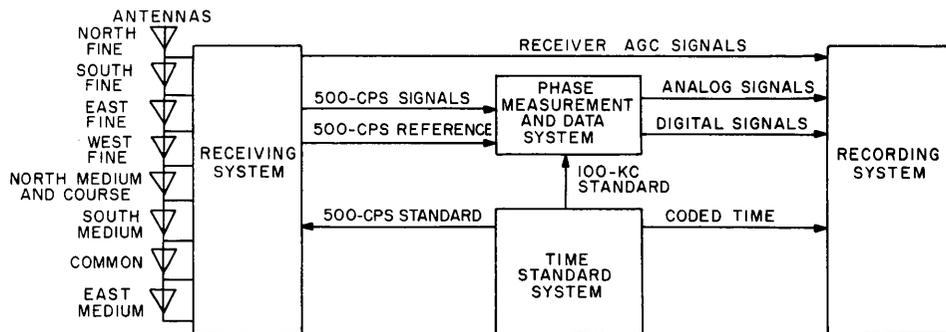


Fig. 2 - Minitrack ground station

Each receiver output is a 500-cps signal bearing the same phase relation to the common noise-free 500-cps reference that one of the two 108-Mc signals from the given antenna pair has to the other. As is shown in Fig. 3, each receiver output signal is passed through a narrow-passband filter, to give the tracking system the desired narrow post-detection bandwidth. From the filter, the signals pass through a buffer chassis and on to the analog phase meters. The signal is converted to a pulse per cycle in the analog phase meters and is available for use in the digital phase meter. The 500-cps reference, as is shown in Fig. 3, is converted to a pulse per cycle in the reference pulse generator, and is fed to the reference inputs of all of the phase meters.

Since the medium and coarse baselines are used only for ambiguity resolution, the reading accuracy needed does not require digital presentation of the data. Both digital and analog presentations are used on the fine channels. The digital presentation allows exact correlation of the data and time, and fast readout of the data to the desired accuracy. The analog presentation shows the character of the data and acts as a backup for the digital

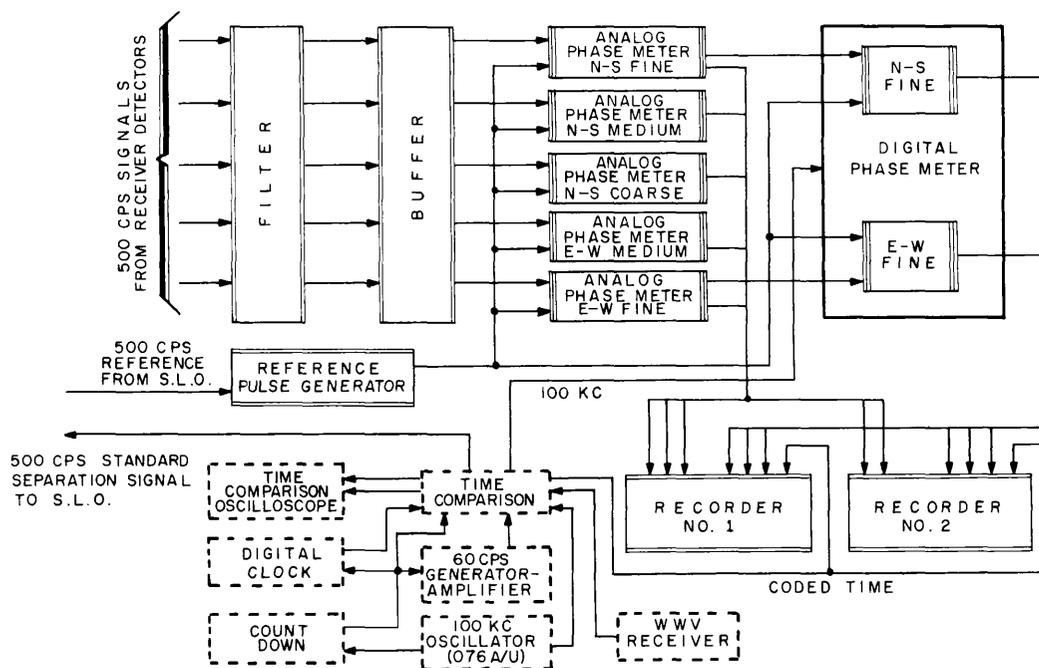


Fig. 3 - Phase measurement and data systems

system. Each output digit of the digital phase meter represents a change in relative phase angle of 0.36 degrees. With the proposed baseline length, the assumed system accuracy of 0.1 mil of space angle is equal to approximately 2 degrees of relative phase. On this basis no significant error will be introduced by the digitalization. The analog phase meters have approximately the same basic accuracy as the digital meters; however, the recorders are accurate to only 1 percent or 3.6 electrical degrees. This recorder accuracy is more than sufficient for ambiguity resolution and for the presentation of the digital information. The internal noise level of the phase measurement equipment is low, less than 0.1 degree rms, and will not influence the readings.

The phase measurement equipment (Fig. 4) will be described in two parts, the first part being a functional description of the electronic components and the second a discussion of the application of Minitrack data to the problem of tracking the satellite.

FILTER AND BUFFER

The signals from the receivers consist of a 500-cps component at a nominal amplitude of 10 volts peak-to-peak, plus noise components to 8000 cps at various levels depending on the received signal strength. The first function of the phase measurement equipment is to pass a receiver signal through a filter designed to provide the narrow post-detection bandwidth. The filter bandwidth between 3-db points is 10 cps, corresponding to an effective post-detection rectangular bandwidth of 8 cps. A schematic of the narrow-passband filter used in the Minitrack system is given in Fig. 5.

The 10-volt peak-to-peak signal from a receiver is divided by approximately 11 by divider R1, R2. This is done so that the change in the inductance of L1 due to the expected variation in signal voltage will be so small that the corresponding signal phase shift may be neglected. The signal is then passed through low-pass filter R3, C1 and is coupled by

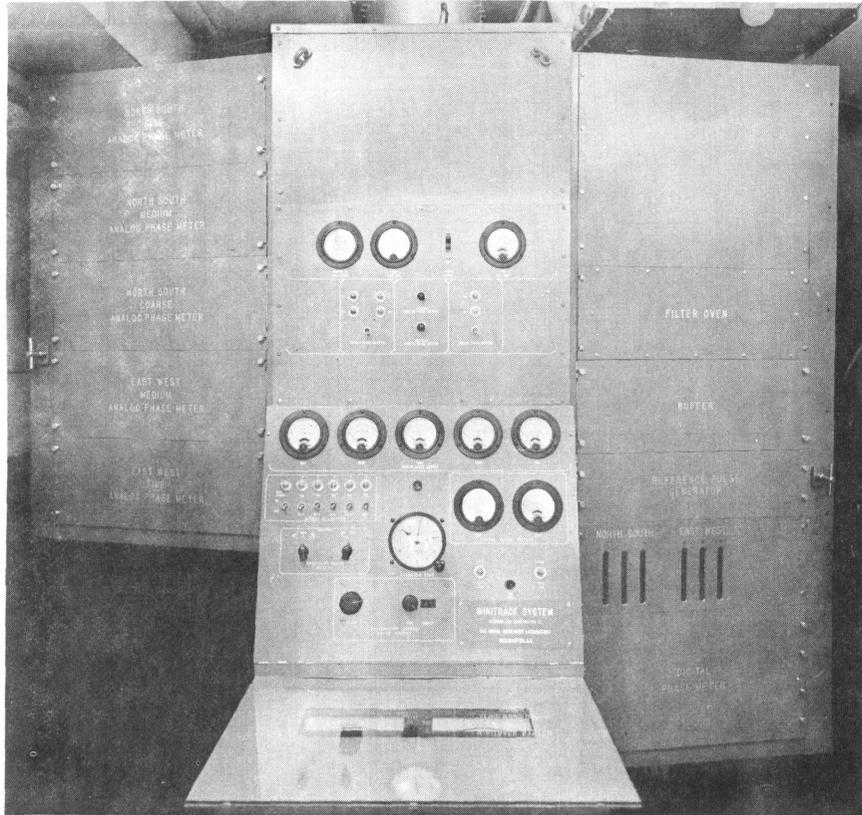


Fig. 4 - Phase measurement portion of Minitrack system

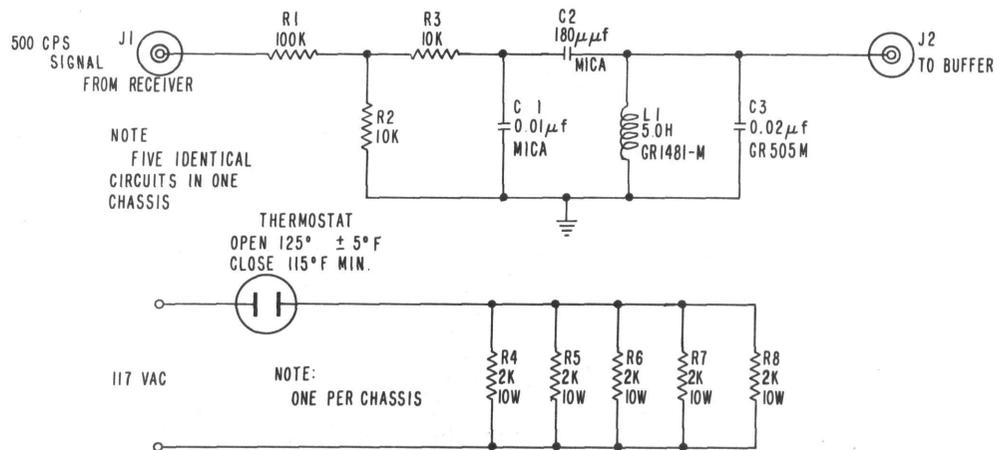


Fig. 5 - Narrow-passband filter employed in Minitrack system

capacitor C2 to the tank L1, C3. Capacitive coupling to the tank is used rather than resistive coupling in order to preserve the Q of the tank, which would be lowered by the loading effect of a coupling resistor. In addition, this filter configuration introduces less attenuation than a resistance-coupled version. The time constant of the low-pass section R3, C1 is chosen to cancel, approximately, the effect of the divider C2, C3 at frequencies above resonance.

Commercial quality parts are used for all components except L1 and C3. These two parts are General Radio secondary standard quality in order to assure the stability of the resonant frequency and to minimize voltage and temperature effects on the filter tuning. The entire five-channel filter is enclosed in an oven and kept at a temperature of approximately $125^{\circ} \pm 4^{\circ}$ F. The inductor L1 is a toroid and is less sensitive to magnetic fields than a laminated inductor; however, it was found necessary to place each inductor in a triple mu-metal shield to prevent cross talk between adjacent inductors.

The output of the filter has a nominal output of 0.5 volt peak-to-peak and is fed directly to the grid of the amplifier stage in the buffer.

The buffer is designed to amplify the filter output without loading the filter and to provide the amplified output on a low-impedance line for distribution to the analog phase meters. There are five identical amplifiers and five cathode followers, as shown in the buffer schematic (Fig. 6). The use of an input grid resistor was avoided in order to minimize loading of the filter; the filter inductor L1 provides a low-resistance path to ground for the grid. The amplifier is a feedback type with approximately 20 db of feedback and a closed-loop gain of about 100. The feedback amplifier is used to provide a stable gain, to maintain linearity, and to keep noise and distortion at a minimum. Cathode followers are used to provide low-impedance outputs for distribution to the five analog phase meters.

REFERENCE PULSE GENERATOR AND ANALOG PHASE METER

As was stated earlier, the relative phase of the 108-Mc signals appearing at the antennas is converted to the relative phase of two 500-cps signals by the time it reaches the phase measurement rack. One of these is a noise-free 500-cps sine wave reference from the local oscillator, and the other is the 500-cps signal output of the receiver detector.

The 500-cps reference from the local oscillator, a sine wave of about 10-volt peak-to-peak amplitude is amplified to approximately 50 volts peak-to-peak in the input amplifier, V101A, of the reference pulse generator (Fig. 7). A single-stage amplifier with approximately 10 db of degeneration is used for this input amplifier. The output of V101A is coupled through cathode follower V101B to a clamping circuit consisting of R12 and back-to-back diodes D1 and D2. The diodes clamp the sine wave at approximately 1/2 volt on each side of the sine wave zero. In addition to providing for clamping action, R12 is of high enough value to prevent loading of the cathode follower.

The clipped sine wave from the clamping circuit is amplified by the feedback pair V102A and V102B. The open-loop gain of approximately 1000 is reduced by feedback to approximately 40, representing a 28-db decrease in nonlinearity, noise, and circuit parameter fluctuations. The output of V102B, a clipped sine wave of 40-volt peak-to-peak amplitude with a rise time of approximately 6μ sec, is coupled through cathode follower V103A to a second stage of back-to-back diode clamping, D3 and D4. The cathode follower V103A is required to prevent R28 from loading V102B. To prevent degeneration of the rise time due to stray capacitance, the value of R28 is kept low. The clamping diodes D3 and D4 are biased by R29, R30, R31, and R32 so that clamping occurs at 1 volt on either side of zero. This 2-volt peak-to-peak square wave out of the clamper is amplified by V103B, a simple triode amplifier with a gain of approximately 30. It is feasible to use a nondegenerative amplifier here despite the relatively high gain needed, since the rise time of the square-wave output of V103B is approximately 1μ sec. With this short rise time, amplitude distortions represent negligible shifts in the time of zero crossing.

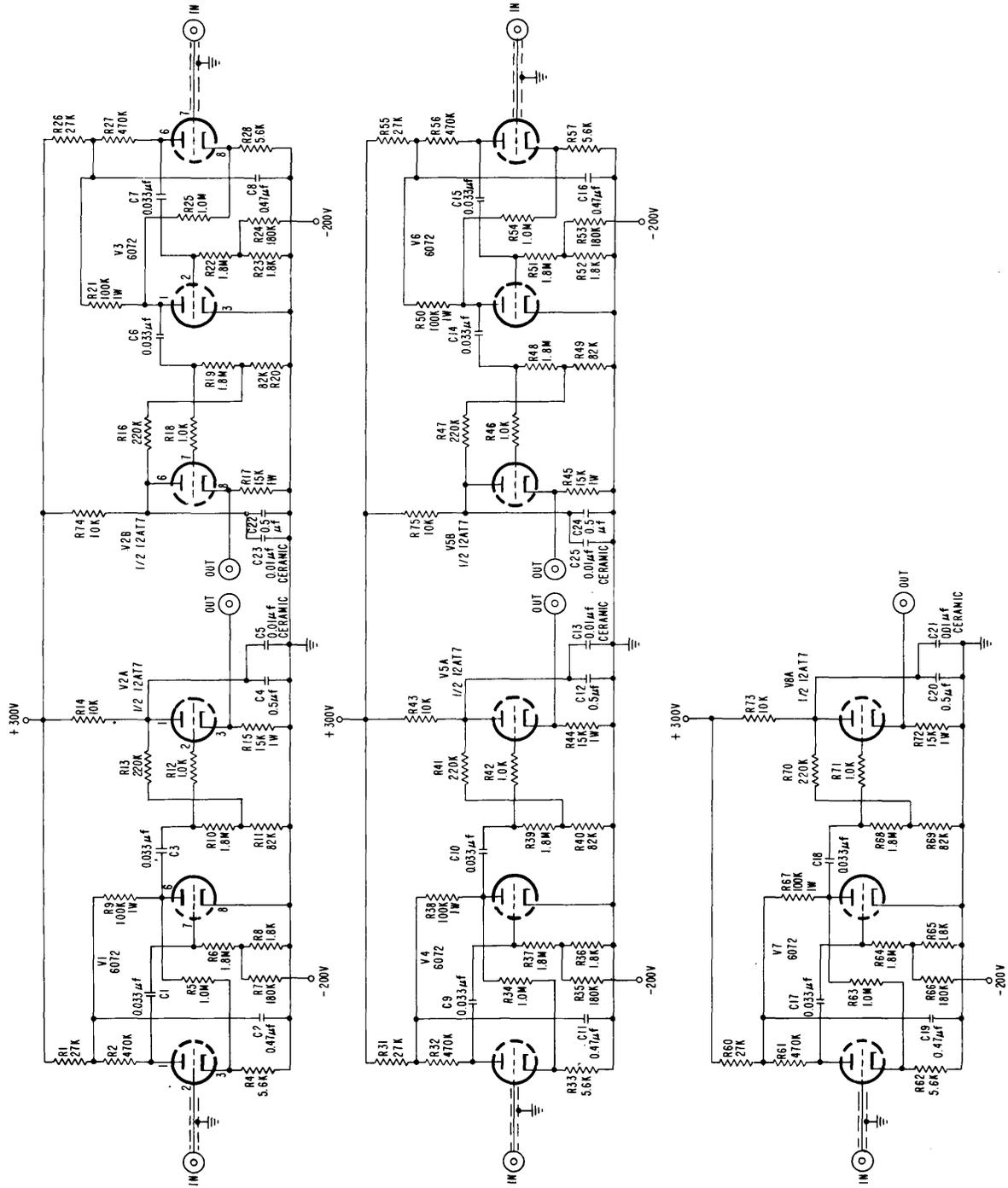


Fig. 6 - Buffer employed in Minitrack system

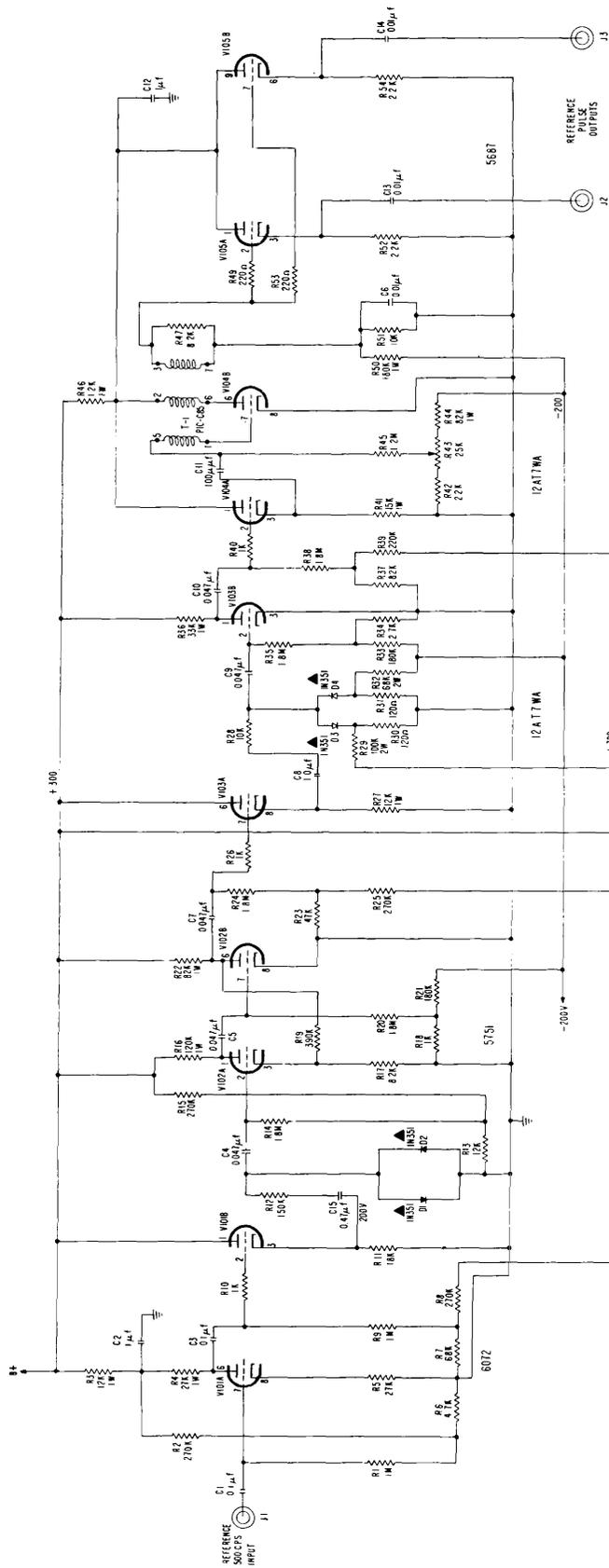


Fig. 7 - Reference pulse generator employed in Minitrack system

▲ DIODES ARE MATCHED PAIR

The circuits of V104A and V104B comprise a series-triggered blocking oscillator. Cathode follower V104A is used to provide isolation between the blocking oscillator and V103B. The square wave from V104A is differentiated by C11, R45 to provide a pulse trigger for the blocking oscillator. In addition, the charge built up on C11 during firing holds the blocking oscillator grid below firing potential until the danger of multiple firing is past. The bias on the grid of V104B is adjusted by potentiometer R43 to cause the blocking oscillator to fire in coincidence with the positive-going zero crossing of the 500-cps sine wave into the unit.

The negative 150-volt 1- μ sec pulse at the plate of V104B is inverted by T1 and fed to two output cathode followers, V105A and V105B. Inversion to a positive pulse is necessary to preserve the leading edge of the pulse. If a negative pulse were applied to the grid, cable capacitance would retard the cathode fall and the more rapidly falling grid would drive the tube to cutoff, thus increasing the source impedance and time constant. The output of one of the cathode followers is distributed to three analog phase meters, the other to two analog phase meters and the digital phase meter.

The reference pulse generator and the analog phase meter are identical through the blocking oscillator, with the exception that the analog phase meter does not have an input amplifier. In the analog phase meter (Fig. 7), the signal at the plate of the blocking oscillator V3B is a negative 150-volt pulse of 1- μ sec duration. This pulse is inverted by transformer T1 and coupled through cathode follower V9 to an output connector for use in the digital phase meter. The five buffer outputs are connected to the corresponding analog phase meter signal inputs.

A bistable switch, V4, receives the 500-cps signal pulse train from the plate of V3B through diode D5 to one grid. The 500-cps reference pulse train from the reference pulse generator enters the analog phase meter through T2 and is inverted and coupled through diode D6 to the other grid of V4. The diodes prevent the switch from firing on the positive overshoot of the triggering pulse, and disconnect the driving circuits from switching transients in the bistable switch. The bistable switch is turned on by the reference pulse and off by the signal pulse. Thus the width of the pulse at the switch plate is proportional to the relative phase of the two (i. e., signal and reference) 500-cps input pulse trains. Voltage divider R52, R53 lowers the levels of the switch output so that the signal goes from below 0 volts to above 60 volts. Capacitor C15 across R52 preserves the fast rise and fall of the signal. Cathode followers V5A and V5B clamp the upper and lower levels at 60 volts and 0 volts (as measured at the output) respectively, through diodes D7 and D8. Wire-wound resistors are used in a divider from B+ to set the grid levels of V5A and V5B for negligible drifting of the clamping level with temperature. The clamping levels are adjustable by means of R65 for the upper value and R56 for the lower. The clamped variable-width pulse is coupled through cathode follower V6A to a low-pass filter consisting of an RC section, a twin T tuned to 500 cps, and a second RC section. The dc output of the low-pass filter is proportional to the relative phase of the reference and the signal. This output is fed through cathode follower V6B, V8A to a connector for meters and recorders.

A floating reference is used to minimize changes in signal output due to changes in heater voltage. The lower clamping level is passed through the same number of cathode followers (V7A and V7B, V8B) as the signal. Potentiometer R81 is an adjustment for zeroing the floating reference. The reference output cathode follower V7B, V8B is designed to have a higher quiescent current than the signal output cathode follower V6B, V8A. Thus as the relative phase of signal and reference increases, and the current in V6B, V8A increases, the current in V7B, V8B decreases and both output cathode followers are always operating in the same general area of the characteristic curves.

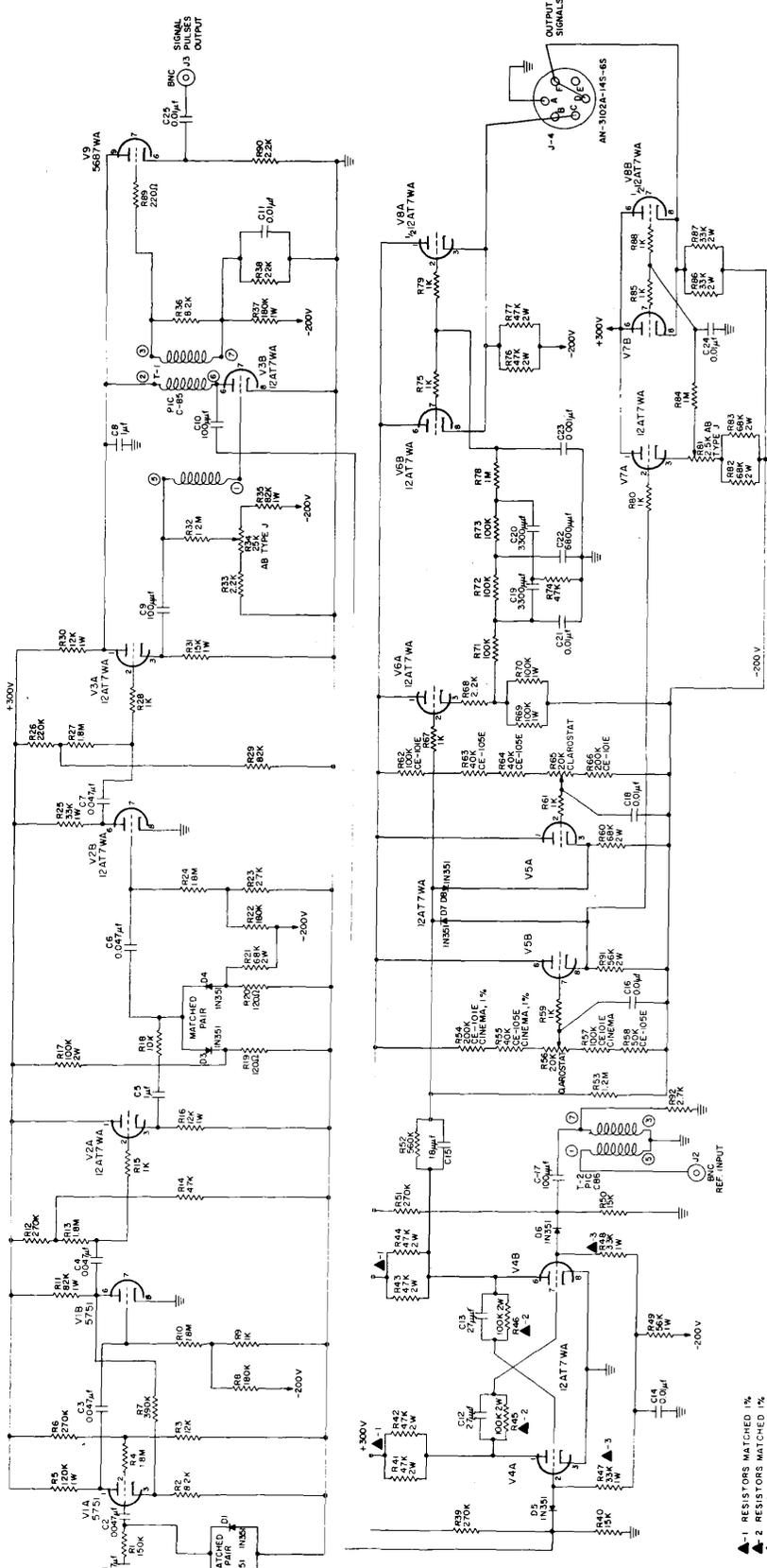


Fig. 8 - Analog phase meter

DIGITAL PHASE METER

The digital phase meter (Fig. 9) measures the phase angle between the signal and the reference by employing a bistable switch to operate a gate which connects a 500-Kc pulse train to a three-decade decimal counter during the time between a reference pulse and a signal pulse. Two channels are provided in the digital phase meter to measure the phase angles of the north-south fine and east-west fine signals. Digital measurements are provided to obtain better resolution of the fine channels than is possible with the analog phase meters. The analog phase meter recordings can be resolved to approximately 3.6 degrees, while the digital phase meter recordings can be resolved to 0.36 degree at the expense of three recording channels for each phase angle to be recorded; the time can be resolved to 0.1 msec because of the synchronization of the time standard and the digital phase meter.

The four sections of the digital phase meter will be described separately.

Reference

The output of the digital phase meter is recorded on a direct-writing recorder which has a frequency response flat to 20 cps and down 3 db at 60 cps. In order to provide output information at a rate within this frequency band, the 500-cps reference pulse train is divided down to 20 cps and digital measurements are made at this frequency. This sampling rate is high enough to extract essentially all the information passed through the filter. The division of the reference pulse train is performed by the two divide-by-five phantastrons V1A, V2 and V1B, V3 (Fig. 9) which divide the reference pulse train by 25 to obtain the basic 20-pps train used to determine the sampling rate. The positive reference pulse train from the reference pulse generator is applied to the suppressor grid of the first phantastron. The first reference pulse arriving at the suppressor triggers the phantastron and initiates the linear rundown of the plate.

The values of R51 and C15 are selected to cause bottoming of the plate rundown, which results in the exponential flyback of the plate voltage to its original quiescent value midway between the fourth and fifth reference pulses after the triggering pulse. The screen output from the first phantastron is a square pulse with its positive rise synchronous with every fifth reference pulse. Cathode follower V1A serves to speed up the flyback. The screen output is differentiated by C18, R66 and the differentiated pulse is used as a trigger on the suppressor grid of the second phantastron. The timing capacitor C17 provides for counting at a slower rate, and the second phantastron divides by five in the same manner as the first phantastron. The screen output of the second phantastron is a square pulse with its positive rise synchronous with every twenty-fifth reference pulse. This pulse, differentiated by C19, R68, triggers a series-fed blocking oscillator, V4. The cathode follower V4A serves to isolate the driving circuit from the pulse on the grid winding of T2. The 20-cps pulse train out of the blocking oscillator is used for two purposes. The train of negative pulses at the plate is used to trigger two bistable switches (see "Switch and Gate"). A train of positive 80-volt pulses taken from the output winding of T2 is coupled through cathode follower V15A to an output jack for transmission to the time comparison unit in the time standard rack. A comparison is made between the 20-cps reference and the 1-cps standard in the time comparison unit, and the phase angle of the reference is adjusted so that every twentieth digital measurement will coincide with the 1-cps standard used for the timing signal on the recorders. This adjustment is made so that the time of any given digital measurement may be known to an accuracy of better than 0.1 msec without requiring that the record be read to this accuracy.

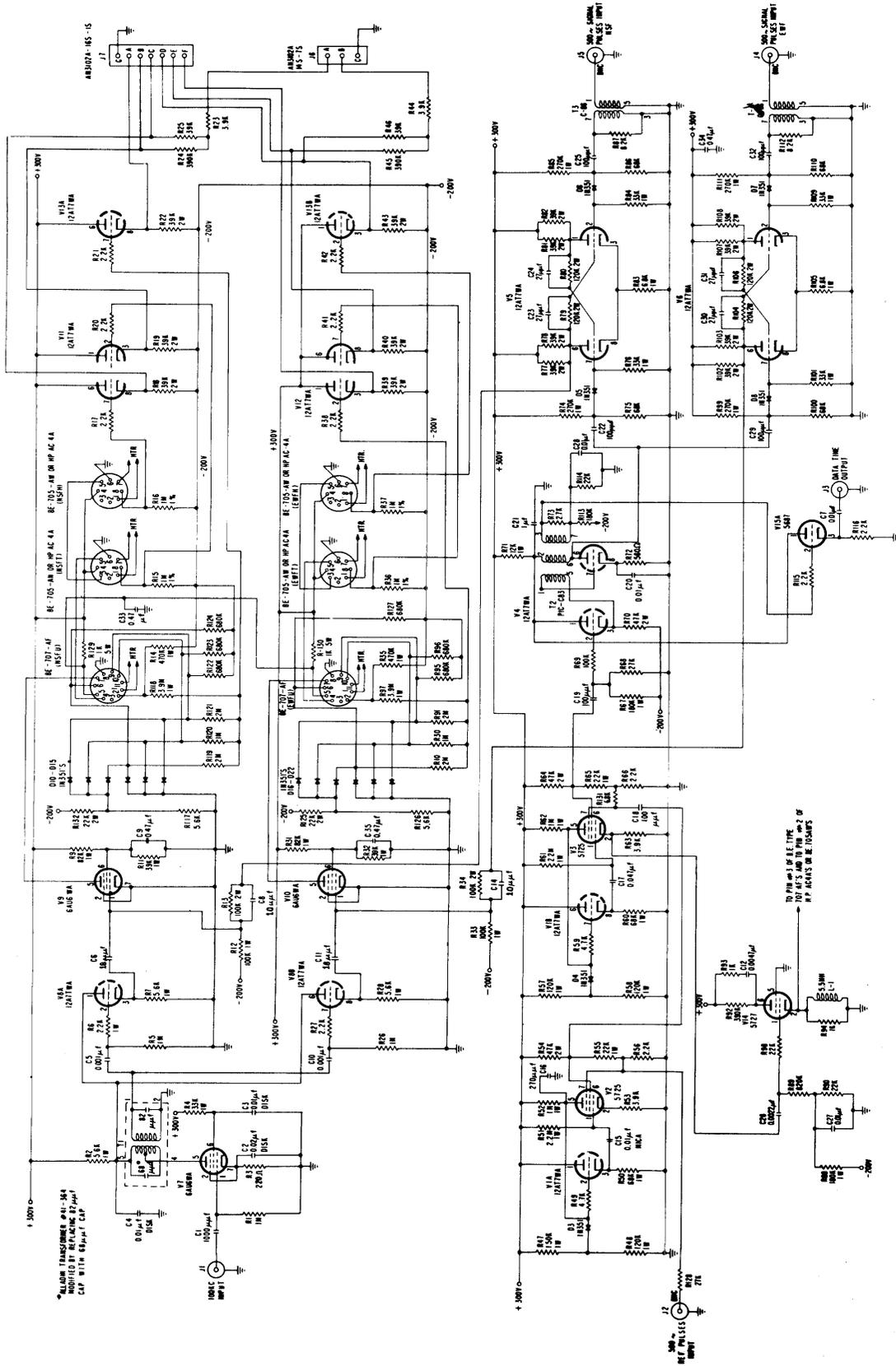


Fig. 9 - Digital phase meter

500-Kc Multiplier

The 500-Kc multiplier utilizes a pentode, V7, driven by a 100-Kc 90-volt peak-to-peak sine wave from the time standard rack. This 100-Kc sine wave comes from the type 076A/U precision oscillator under normal conditions, and from the 100-Kc auxiliary oscillator in the time comparison unit in the event the 076A/U fails. A high-Q double-tuned circuit, T1, in the plate circuit of V7, is tuned to 500-Kc and provides a 120-volt peak-to-peak sine wave at the secondary which is coupled to the grids of cathode followers V8A and V8B. These cathode followers clip the negative portion of the 500-Kc sine wave, thus forming 60-volt pulses to be passed through the gate to the two decimal counters.

Switch and Gate

Two bistable switches (V5 and V6) and two gates (D1 and D2) are provided to connect the 500-Kc pulse train to the decimal counters. The 20-cps reference pulse train from the plate of blocking oscillator V4B is coupled to the grids of bistable switches V5 and V6 to turn them on. The 500-cps signal pulse train from the appropriate analog phase meter is inverted by transformer T3 or T4 and fed to the remaining grid of the associated switch to turn it off. The coupling diode pairs D5, D6 and D7, D8 decouple the driving circuits during the switch transients and clamp the positive overshoots of the triggering pulses to prevent them from triggering the switch at the wrong time. It is unnecessary to divide the signal pulse train down to 20 cps, because once the first signal pulse following a reference pulse has turned the switch off, the remaining signal pulses have no effect until another reference pulse has turned the switch on again. The level of the gating signal from the plates of the switches is lowered by divider R12, R13 so that the upper level of the signal to the grid of the counter drivers V9 and V10 is at ground level, and the lower level drives the grid well below cutoff. Thus when the switch is on, the 500-Kc pulses are coupled into the counter drivers.

Counters

Each of the two decimal counters is made up of a driver (V9 or V10), one high-frequency counter (Berkeley 707AF) and two medium-frequency counters (Hewlett-Packard AC-4A). All the counters are reset by V14, a thyatron which is triggered by the positive rise of the cathode of V3 approximately 5 msec before a count is to be made. A thyatron is used to provide the low dc resistance necessary to prevent voltage change in the reset bus due to changes in state of the binary stages in the counters. The resistor-diode matrix connected to each of the two high-frequency counters is used to form an analog representation of the counter digital output. As a result of the method of permutation used in the Berkeley 707AF counter, the second, third, and fourth stages each have four stable states. Diodes D10 through D15 clamp the upper and lower levels of the output of the associated counter stage to prevent the multiple stable states from causing error in the analog representation. Since this problem does not exist in the medium-frequency counters, a simple resistor matrix forms the analog representation which is brought out on pin 8 of these counters. Cathode followers V11, V12, and V13 provide these analog voltages on low-impedance buses through an output connector to the Sanborn recorder amplifier as a three-digit number (0 to 999). This number, a measure of the direction cosine of the angular position of the satellite in terms of percentage of antenna baseline length, will be explained in the section of this report headed "Data Handling." The tens and hundreds counter outputs are combined by a resistor matrix and fed through an output connector to meters on the control panel to give an approximate indication of the phase meter reading.

A detailed test specification for the components of the phase measurement system is given in Appendix A. A test generator, used to simulate the signals normally fed to one complete phase measurement channel in the Minitrack system, is described in Appendix B.

RECORDING SYSTEM

The information presented by the phase measurement system for recording is in the form of five analog phase readings and two digital phase readings. A single recording channel is sufficient for each analog phase reading, but each digital phase reading requires three recording channels. In addition, five recording channels are needed to record the AGC voltages in the five receivers. Two Sanborn model 158-5475 eight-channel recorders are used to provide the Minitrack recordings. These are graphic recording instruments, each having eight D'Arsonval-movement galvanometers driving hot-wire styli over plastic-coated paper. The resulting records are in rectilinear coordinates instantaneously available for reading, permanent, and of excellent line definition.

Timing information in the form of relay closures in a coded time sequence is received from the time standard rack and is used to energize the timing stylus in the margin of the record. This stylus records a 60-cps signal during the 50-msec "on" period of the time standard relay. A sample record from one of the recorders is given in Fig. 10, and a photograph of the recorders in Fig. 11.

DATA HANDLING

Minitrack is a practical application of radio interferometry to measure the angular position of an earth satellite with a resolution of 4 seconds of arc and to relate this positional information to time with an accuracy of 1 msec referred to WWV. For the purposes of this discussion, the term "Minitrack data" refers to the difference between the radio paths from the satellite to each of two ground antennas, measured in wavelengths. These data may be divided by the antenna spacing to obtain the cosines of the angles from the horizontal to the various satellite positions corresponding to the data points. Each of these angles locates the satellite in a plane defined by the baseline between the appropriate antennas and the lines from these antennas to the satellite. To locate the satellite in three dimensions, it is necessary to have an additional antenna pair with a baseline orthogonal to the first antenna pair. The two baselines are chosen to lie in the north-south and east-west directions in order to simplify geographic location of the satellite.

Measurement of the radio path difference is made in the Minitrack system by comparing the phase angle of the signal received on one antenna to that of the signal received on the other antenna; the relative phase angle will be zero whenever the radio path difference is an integral number of wavelengths. As the satellite passes through the antenna pattern, the relative phase will cycle from zero to full scale for each wavelength added to the radio path difference. If θ is the angle of the satellite measured from zenith (Fig. 12), $K+a$ is the radio path difference in whole plus fractional wavelengths, respectively, and d is the antenna baseline in wavelengths, then

$$\sin \theta = \frac{K+a}{d} . \quad (1)$$

For small values of θ (zenith),

$$\theta = \frac{K+a}{d} \text{ radians} . \quad (2)$$

For $K = 1$ and $a = 0$,

$$\theta = \frac{1}{d} . \quad (3)$$

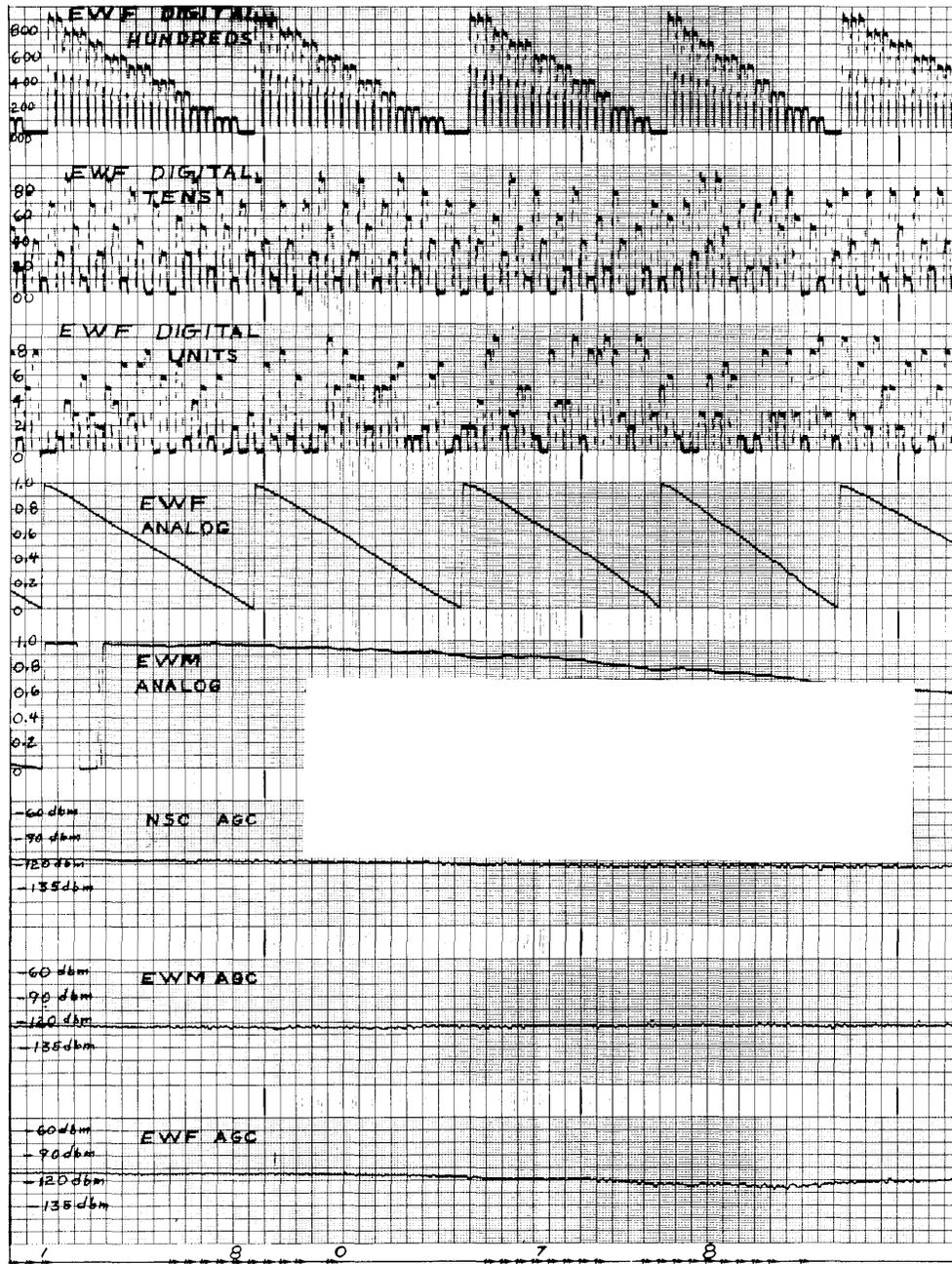


Fig. 10 - Sample record

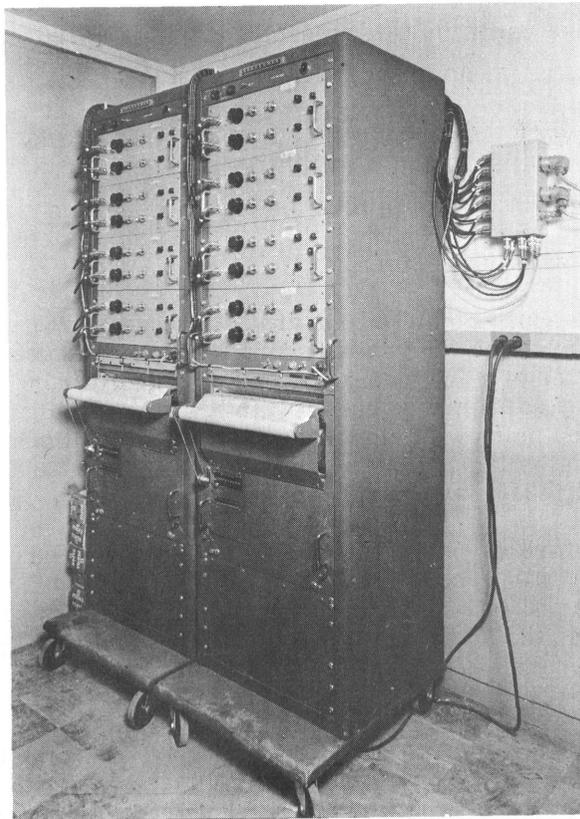


Fig. 11 - Minitrack recorders

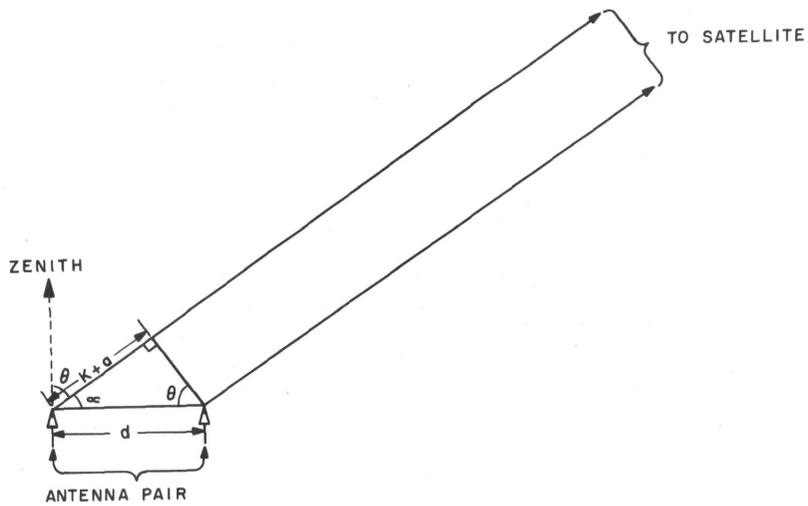


Fig. 12 - Minitrack angular relationships

Converting θ to degrees and using the fine antenna spacing of 54.90 wavelengths (500 feet) gives

$$\frac{\theta}{57.2} = \frac{1}{54.9}, \quad (4)$$

$$\theta = 1.04^\circ.$$

Therefore, for each wavelength change in $K+a$ the satellite must move through 1.04 degrees when near zenith. It should be noted that $90^\circ - \theta = \alpha$, and $\sin \theta = \cos \alpha$, where $\cos \alpha$ is the direction cosine of the satellite position.

The antenna pattern is approximately 10 degrees wide east to west and 100 degrees wide north to south; therefore, the Minitrack record from the east-west fine channel will have approximately 10 cycles of a sawtooth wave and the record from the north-south fine channel might have as many as 90 cycles of a sawtooth wave. Ambiguity is resolved by the use of additional antenna pairs with closer spacing. One additional antenna pair with a spacing of 7.028 wavelengths is used in the east-west direction, and two additional pairs with spacings of 7.028 and 1.318 wavelengths are used in the north-south direction.

As the satellite passes from west to east through the major lobe of the antenna, the east-west fine output signal will cycle from zero to full scale approximately ten times, and the medium channel output will cycle from zero to full scale approximately one and one-half times. Therefore, the signal from the medium channel can be used to determine the whole number of wavelengths to be added to the reading of the digital phase meter to define a data point.

For the fictitious case of a satellite passage from north to south, the north-south fine signal will cycle from zero to full scale approximately 90 times, the medium approximately 10 times, and the coarse approximately two times. If the coarse signal could be relied upon to be accurate to one part in 100, it could be used alone to determine the wavelength on the fine record corresponding to a data point. However, owing to the possibility of system drift and the probable recorder inaccuracy of at least 1 percent, it was deemed necessary to use an additional antenna pair and employ two steps to remove ambiguity in the north-south measurement. For a satellite passage from west to east, the north-south signals could be unchanging and their values (fine, medium, and coarse) would be used, together with a graph plotting the three signals from 50 degrees north of zenith to 50 degrees south of zenith, to determine the north-south K .

The Minitrack system will be connected so that the north-south phase meter readings will increase for a transmitter passage from south to north and the east-west phase meter readings will increase for a transmitter passage from west to east. The first east-west fine phase meter zero-reading west of zenith will be designated as east-west fine 50; other east-west fine phase meter zero-readings will be numbered from 50, increasing to the east and decreasing to the west. The first north-south fine phase meter zero-reading south of zenith will be designated as north-south fine 50; other north-south fine phase meter zero-readings will be numbered from 50, increasing to the north and decreasing to the south. These zero-reading numbers are the values of K . The actual fine phase meter reading is the value of a , and the complete phase reading will be the sum $K+a$, where K corresponds to the phase meter zero-reading just west or south of the particular a .

The procedure for putting the recorded data in a form suitable for transmission and computation would be as follows:

- (1) Determine the segment of recorded data during which the satellite is passing through the main antenna lobe.
- (2) Read the east-west medium fractional wavelength at a selected second from the analog record.

(3) Refer to a plot of wavelengths versus satellite angles for east-west medium and east-west fine channels and determine the K corresponding to the reading from (2) above.

(4) Read the east-west fine fractional wavelength at the selected time from the digital record.

(5) Add the K from (3) to the fractional wavelength (a) from (4) to obtain the desired east-west phase reading at the selected time.

(6) Read the north-south coarse fractional wavelength at the selected time from the analog record.

(7) Refer to a plot of wavelengths versus satellite angles for the north-south channels and determine which north-south medium K corresponds to (6).

(8) Read the north-south medium fractional wavelength at the selected time from the analog record.

(9) Add the medium K from (7) to the fractional wavelength from (8) to obtain the complete north-south medium phase reading.

(10) Refer to the plot of K versus satellite angles for the north-south channels and determine which north-south fine K corresponds to (9).

(11) Read the north-south fine fractional wavelength from the digital record.

(12) Add the K from (10) to the a from (11) to obtain the complete north-south fine phase reading at the selected time.

(13) The results from steps (5) and (12) are one pair of phase readings.

(14) Succeeding angles would be read in simpler fashion since ambiguity resolution would no longer be required. Steps (1) through (3) and (6) through (10) would be deleted. Steps (5) and (12) would be modified in the following way: add or subtract 1 to the whole number of wavelengths (K) for the preceding reading each time the fine data passes through full-scale or zero.

A procedure has been set up for converting the data into a message, consisting of six digit "words," suitable for teletyping back to the central computing facility. The body of the message is prepared so that when it is printed on a teletypewriter the data appear in two columns of six digits each. The first line contains a six letter abbreviation of the station location followed by a space and a six digit date. The first two digits of the date are the year, the middle two are the month, and the last two are the day of the month. The second line contains two six-digit words which present the time of the first and the last reading. The time readings are given so that the first two digits give hours in the twenty-four hour system, the middle two digits are the minutes, and the last digits are the seconds.

The third line contains two six-digit words giving the calibration data before the satellite passage. The left-hand word gives the east-west fine digital phase meter reading and the right-hand word gives the north-south fine digital phase meter reading for a standard rf input to the Minitrack receiver. The first three digits of these two words will be zeros, and the last three digits will be the readings of the phase meters. The fourth line contains two six-digit words giving the calibration data after the satellite passage in the same manner as for the third line.

The first four lines are repeated as the last four lines in order to give a redundancy check of the teletype transmission. The remaining lines list the actual Minitrack data

with the east-west data being on the left and the north-south data being on the right. The first digit of each word is 0, the next two digits are the value of K , and the last three digits are the value of a .

The reading interval will normally be 1 second; however, if 1-second readings would cause more than approximately 25 readings to be taken, an interval of 2 or 3 seconds will be used to limit the maximum number of readings to about 20. When data for a whole reading or part of one are not obtainable, slant symbols will be used in place of digits.

The Minitrack data permit the computation of the unit vector directed toward the satellite at any given instant of time in terms of the Minitrack coordinate system. It is then necessary to transform this unit vector by means of a matrix so that it will be referred to the inertial coordinate system. For practical reasons, this should be done in two stages: (1) to take account of the station adjustment errors, the phase shift by the narrow-band filter due to satellite velocity, and the latitude (all of which are peculiar to each station); (2) to take account of the longitude of the observing station, which is a function of the time of observation. Calibration tests must be performed to provide the elements of the matrix which will transform a vector referred to the actual Minitrack station to one referred to an ideally adjusted station. This relieves the problem of critical adjustment of the Minitrack system, leaving only as an important consideration the stability of the equipment between calibration tests.

SUMMARY

In the phase measurement portion of the Minitrack system, precautions have been taken to assure precision, resolution, and stability compatible with the desired Minitrack accuracy, and to provide the low maintenance requirements desirable for field instrumentation. The digital method of phase measurement provides the high degree of resolution common to digital systems in general, and in addition provides easy and precise time correlation owing to its synchronous operation with the time standard. The analog method of phase measurement presents an easily understood picture of satellite motion, and ambiguity resolution is readily obtained.

ACKNOWLEDGMENTS

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* * *

APPENDIX A

Test Specifications for Phase-Measurement Equipment

Test specifications for the individual electronic chassis are provided to assure correct operation and to aid in trouble-shooting. Input signals are specified and resultant outputs are indicated; the oscillographic investigations of waveforms are made with a Tektronix type 535 oscilloscope. Voltage charts are also included, to give nominal voltages at tube terminals under specified conditions; these voltages were measured with a Hewlett Packard 410B vacuum tube voltmeter which has a 10-megohm input impedance. In some cases the measured voltage differs from the actual operating voltage because of loading by the ten-megohm impedance of the voltmeter, and care must be used in determining actual operating conditions based on the voltages in the charts. The test specifications are based upon the individual chassis being supplied with +300 vdc and -200 vdc from Power Designs, Inc., power supplies or the equivalent, and 6.3 vac with the center tap grounded. The B+ and B- voltages should be set to within 1 v of the nominal value. Where possible, specifications are written involving only one chassis, but some units, i. e., the analog phase meter and the digital phase meter, require other parts of the system for adequate test and evaluation.

The individual specifications are as follows:

Filter and Buffer

The filter and buffer must be tested as a unit. Connect power to the two units and connect the filter outputs to the corresponding buffer inputs. (Note: the filter must be supplied with nominal 117 vac). The current drain should be approximately 30 ma at +300 vdc, 10 ma at -200 vdc, 2.6 a at 6.3 vac, and 0.2 a at 117 vac. The tube element voltages should agree approximately with the voltage chart for the buffer (Table A1). The magnitude of any buffer output (no input to filter) should be less than 30 mv peak-to-peak and be predominantly 60 cps.

Connect a 500-cps 10-v peak-to-peak signal to one filter input; the corresponding buffer output should be greater than 50 v peak-to-peak, and the 500-cps component of any of the other outputs should be less than 20 mv peak-to-peak. Repeat this test for each input. The maximum response should occur at 500 ± 1 cps and the bandwidth between the 3-db points should be 10 ± 1 cps.

The internal temperature of the filter should not vary more than 8° F after a 12-hour warmup.

Reference Pulse Generator

Connect power to the chassis; the current drain should be approximately 40 ma at +300 vdc, 10 ma at -200 vdc, and 2.1 a at 6.3 vac. Tube element voltages should agree approximately with the voltage chart for the reference pulse generator (Table A2).

Connect a 500-cps 10-v peak-to-peak signal to the input; the signal at the cathode of the blocking oscillator driver (Pin 3, V104) should be a square wave with an amplitude of 50-v peak-to-peak or more, and a rise time of approximately 1 μ sec, and should have a pulse on the positive rise at the time the blocking oscillator fires. Adjust R43 to cause the blocking oscillator to fire at the positive-going zero crossing of the signal at the

cathode of the blocking oscillator driver (Pin 3, V104). The pulse outputs should be of approximately +150-v amplitude and be about 2 μ sec wide at the base. The time jitter of the output pulse should be less than 1/4 μ sec.

TABLE A1
Voltage Chart for Buffer

	Pin 1	2	3	4	5	6	7	8	9
V1	95	0	2	Htr.	Htr.	95	-1.5	Gnd.	Htr.
V2	255	67	70	Htr.	Htr.	255	67	70	Htr.
V3	95	0	2	Htr.	Htr.	95	-1.5	Gnd.	Htr.
V4	95	0	2	Htr.	Htr.	95	-1.5	Gnd.	Htr.
V5	255	67	70	Htr.	Htr.	255	67	70	Htr.
V6	95	0	2	Htr.	Htr.	95	-1.5	Gnd.	Htr.
V7	95	0	2	Htr.	Htr.	95	-1.5	Gnd.	Htr.
V8	255	67	70	Htr.	Htr.	-	-	-	Htr.

TABLE A2
Voltage Chart for Reference Pulse Generator

	Pin 1	2	3	4	5	6	7	8	9
V101	300	55	65	Htr.	Htr.	195	5	7	Htr.
V102	135	11	14	Htr.	Htr.	150	-1	Gnd.	Htr.
V103	175	-2.5	Gnd.	Htr.	Htr.	300	37	48	Htr.
V104	285	68	85	Htr.	Htr.	285	-4 to -54	Gnd.	Htr.
V105	285	-10	6	Htr.	Htr.	6	-10	Htr.	285

Analog Phase Meter

The filter and buffer chassis must be used to supply a "signal" and the reference pulse generator must be used to supply a "reference" to the analog phase meter. Connect power to the various chassis and make the necessary interconnections. The current drain in the analog phase meter should be approximately 75 ma at +300 vdc, 50 ma at -200 vdc, and 3.3 a at 6.3 vac. Connect a 500-cps 10-v peak-to-peak signal to the buffer-filter channel feeding the signal input of the analog phase meter; connect a Weston Model 901 60-v voltmeter to the analog phase meter output, J4. The tube element voltages should agree approximately with the analog phase meter voltage chart (Table A3). The signal at the cathode of the blocking oscillator driver (Pin 3, V3) should be a square wave with an amplitude of 50 v peak-to-peak or more, and a rise time of approximately 1 μ sec, and should have a pulse on the positive rise at the time the blocking oscillator fires. Adjust R34 to cause the blocking oscillator to fire at the positive-going zero crossing of the signal at the cathode of the blocking oscillator driver. The pulse output amplitude should be approximately +100 v, with a duration of about 2 μ sec at the base, and with a time jitter of less than 1 μ sec.

Connect a voltmeter between ground and pin B or C of the output connector J4, and adjust R56 for an indication of 0 v (an adjustment of ± 6 v should be possible). Connect the voltmeter between ground and pin D or F of J4 and adjust R81 for an indication of 0 v (an adjustment of ± 5 v should be possible).

Disconnect the 500-cps input from the filter and connect it instead to the reference pulse generator. Adjust R65 for full-scale indication on the Weston Model 901 voltmeter (an adjustment of full scale ± 6 v should be possible).

Connect the 500-cps 10-v peak-to-peak signal to both the reference pulse generator input and the selected filter input; the Weston Model 901 voltmeter should now show a reading of approximately one-third of full scale.

TABLE A3
Voltage Chart for Analog Phase Meter

	Pin 1	2	3	4	5	6	7	8	9
V1	135	11	14	Htr.	Htr.	150	-1	Gnd.	Htr.
V2	300	37	48	Htr.	Htr.	175	-2.5	Gnd.	Htr.
V3	220	68	76	Htr.	Htr.	220	-4 to -54	Gnd.	Htr.
V4	245	-27	Gnd.	Htr.	Htr.	67	0+	Gnd.	Htr.
V5	300	60	64	Htr.	Htr.	300	-5	0	Htr.
V6	300	-1	3	Htr.	Htr.	300	-4	0	Htr.
V7	300	0	3	Htr.	Htr.	300	-4	0	Htr.
V8	300	-4	0	Htr.	Htr.	300	-4	0	Htr.
V9	-	-	-	Htr.	Htr.	0	-22	Htr.	220

Digital Phase Meter

The filter, buffer, and analog phase meter will be required to supply the "signal" pulse train to one channel of the digital phase meter; the reference pulse generator is necessary to supply the "reference" pulse train to the reference input of the digital phase meter. The digital phase meter requires an additional 100-Kc input at 90 v peak-to-peak which must be phase-locked to the 500-cps signals; time standard system components may be used to obtain these signals.

Connect power to the various chassis, and make the required phase measurement inter-unit connections. Connect a 100-Kc 90-v peak-to-peak signal to J1; connect the reference pulse generator output to J2, and connect the analog phase meter "signal" pulse train output to both J4 and J5. Connect a 500-cps (phase-locked to the 100-Kc input) 10-v peak-to-peak signal to the input of the selected filter-buffer channel. The approximate current drain for the digital phase meter will be 275 ma at +300 vdc, 55 ma at -200 vdc, and 16 a at 6.3 vac. The tube element voltages should agree approximately with the voltage chart for the digital phase meter (Table A4) and the counters should all read zero. Adjust the tuning of transformer T1 to make the output of cathode followers V8A and V8B maximum; their output voltages should be more than 50 v peak-to-peak, have the appearance of a half-wave rectified sine wave, and a frequency of 500-Kc.

The 500-cps reference pulse train is fed to the two phantastrons V1A,V2, and V1B,V3, which divide the reference frequency by 25 to obtain the basic 20-cps signal used to

TABLE A4
Voltage Chart for Digital Phase Meter

	Pin 1	2	3	4	5	6	7	8	9
V1	300	134	137	Htr.	Htr.	300	150	153	Htr.
V2	11	11	Htr.	Htr.	142	46	4	-	-
V3	11	11	Htr.	Htr.	150	46	4	-	-
V4	255	-26	-23	Htr.	Htr.	255	-23	0	Htr.
V5	260	25	48	Htr.	Htr.	140	48	48	Htr.
V6	260	25	48	Htr.	Htr.	140	48	48	Htr.
V7	-40	1	Htr.	Htr.	235	240	1	-	-
V8	235	-10	20	Htr.	Htr.	235	-10	20	Htr.
V9	-40	Gnd.	Htr.	Htr.	210	120	Gnd.	-	-
V10	-40	Gnd.	Htr.	Htr.	210	120	Gnd.	-	-
V11	300	-1 to +4	1 to 6	Htr.	Htr.	300	-1 to +4	1 to 6	Htr.
V12	300	-1 to +4	1 to 6	Htr.	Htr.	300	-1 to +4	1 to 6	Htr.
V13	300	-1 to +4	1 to 6	Htr.	Htr.	300	-1 to +4	1 to 6	Htr.
V14	-20	1	Htr.	Htr.	Gnd.	300	-	-	-
V15	255	-22	0	Htr.	Htr.	-	-	Htr.	-

cycle the digital phase meter. The waveform at the cathode of V1A should be a linear rundown from and an exponential return to approximately 134 volts. The rundown should be triggered by a reference pulse and the exponential rise should occur centered between the fourth and fifth reference pulses after the rundown is initiated. The screen output from the first phantastron pin 6, V2 should be a square pulse with its positive rise synchronous with every fifth reference pulse. The second phantastron V1B, V3 is triggered by a positive pulse obtained by differentiating the pulse from pin 6 V2. The waveform at the cathode of V1B should be a linear rundown from and an exponential return to approximately 150 volts. The rundown should be triggered by the positive pulse from V2, and the exponential rise should occur centered between the fourth and fifth positive pulses after the rundown is initiated. The screen output from the second phantastron (pin 6, V3) should be a square pulse with its positive rise synchronous with every fifth positive pulse from the first phantastron and, therefore, synchronous with every twenty-fifth reference pulse. This pulse is also differentiated and is then used to trigger a blocking oscillator, V4, used to operate the two bistable switches for the two digital phase meter channels. The output of the blocking oscillator is taken from a winding of transformer T2, connected for a positive pulse, and is fed to the grid of V15A which is a cathode follower used to supply the pulse on a low-impedance line to the time standard system. The 20-cps data time output pulse should be of approximately +80-v amplitude and be about 2 μ sec wide at the base.

Connect the 500-cps signal to both the reference pulse generator and the selected filter-buffer channel; the digital phase meter should indicate a reading on both channels of approximately 330.

Connect the 500-cps signal to the reference pulse generator, and connect a 500.1-cps 10-v peak-to-peak signal to the filter-buffer; note that the digital phase meter is now cycling from 999 to 000 at a rate of approximately 0.1 cps. The outputs to the recorder should be staircase analogs of the decimal count indicated by the counters. Each step should be within ± 20 percent of $1/9$ of the change from 0 to a count of 9.

The digital phase meter outputs through J6 should be connected to two 1-ma ammeters and these meters should cycle from full scale to zero as the digital phase meter counters cycle from 999 to 000. The meters should agree with the counters to within ± 5 percent of full scale. The meter mechanical zero may be adjusted to cause the meter to indicate zero for a counter reading of 000.

Phase Measurement Equipment

The phase measurement portion of the Minitrack system is housed in an equipment rack. A schematic of the signal wiring and a schematic of the power wiring in the phase measurement rack are given in Figs. A1 and A2, respectively.

The phase measurement equipment must meet the following specifications when incorporated into the Minitrack system. The specifications refer to operation at a standard 60-cps power input of 117 ± 5 v and at an ambient temperature between 60° and 90° F.

Phase Drift — After a warmup period of 24 hours, the total drift of any phase meter, analog or digital, shall be less than ± 0.7 degrees within the succeeding 12 hours. All inputs shall be fed from the reference signal during this test.

Noise — The rms value of the noise output from the analog phase meters shall be less than 0.05 degree. The gate jitter of the digital phase meter shall be less than 0.15 degree peak-to-peak. All inputs shall be fed from the reference signal during this test.

Linearity — The analog phase meters shall be linear within 0.5 percent of full scale and the digital phase meter within one count (0.36 degree).

Regulation — For a variation of input power of ± 10 percent, the outputs of the digital phase meter shall not change by more than one count, and the outputs of the analog phase meters shall be constant within ± 0.5 percent of full scale.

Input Signal Amplitude — A variation of the input voltage at the filter from 4 volts peak-to-peak to 12 volts peak-to-peak shall not cause more than ± 0.1 percent of full-scale change in the output indication of the phase meters.

APPENDIX B Test Generator

John W. Ryan

The test generator is a 100-Kc and 500-cps sinusoidal signal source designed to simulate the signals fed to the phase measurement equipment by the other components of the Minitrack system. Its circuitry is mounted in a nominal 5×17 inch chassis. There is one control on the panel: a dial calibrated from 0 to 100 to indicate one 360-degree rotation.

A 100-Kc and two 500-cps output BNC connectors are located on the back of the chassis. One of the 500-cps outputs provides a constant-phase signal, the other a variable-phase signal; all three signals are phase-coherent. The variable-phase signal can be varied from 0 to 360 degrees in phase angle with respect to the constant-phase signal by rotating the dial on the panel.

The 100-Kc and 500-cps input BNC connectors are located on the back of the chassis for use when an external signal is desired rather than one from the test generator. Toggle switches provide a means of shifting from one to the other.

The 500-cps variable-phase signal simulates the satellite signal, and the constant-phase 500-cps signal simulates the reference signal from the local oscillator. In addition, the test generator provides a 100-Kc signal input for the digital phase meter.

The test generator is designed to be a part of the equipment rack used in the Minitrack system operator training program. This rack is a standard relay rack with filter, buffer, analog phase meter, reference generator, digital phase meter, and two power supplies mounted to provide an operating equivalent of the phase measurement system. Use of the test generator permits Minitrack phase measurement training without receiver or time standard equipment.

The test generator (Fig. B1) reduces a 100-Kc signal to 500 cps by a frequency dividing process. First, two Berkley 705-AF counters successively divide the frequency by 10 to obtain a 1000-cps signal, and an EECO Type Z-90059 binary counter then divides this frequency by 2 to produce a 500-cps signal. Next, the square-wave output of the binary counter is filtered with a three-section low-pass RC filter to produce a 500-cps sine wave which feeds a Reeves Type R-150 resolver connected as a phase shifter. Through the use of an output before and after the resolver, a constant and a variable phase output are obtained.

The internal 100-Kc signal is provided by a crystal oscillator, V1A. At the output of V1A there is a tunable tank circuit resonant at 100-Kc. V1B is a cathode follower to feed the 100-Kc output to the digital phase meter, and to supply a 100-Kc signal at low impedance to V2, a Schmitt Trigger. The square-wave output of the Schmitt Trigger goes to the input of a Berkeley 705-AF counter, and is counted down to 10 Kc. This 10-Kc signal is fed to the input of another Berkeley Type 705AF counter and counted down to 1000 cps, then fed to the EECO binary counter and divided by 2 to obtain a 500-cps square wave. The square wave is passed through a three-section low-pass RC filter to produce a 500-cps sine wave which is amplified by V3A. The output of V3A is fed to the inputs of cathode followers V3B and V4A. The V4A output goes to a Reeves Type R-150 resolver, connected as a conventional phase shifter, the primary of which is resonated to 500 cps. The output

from this resolver goes to the input of cathode follower V4B, which provides a low-impedance output path for the desired 500-cps variable-phase sine wave. Rotating the resolver shaft will shift the phase of this signal from 0 through 360 degrees. Another cathode follower, V3B, provides a low-impedance output path for the 500-cps constant-phase reference signal.

Checking of the phase shift every 18 degrees on the panel dial showed that the phase error of the variable-phase output is limited to ± 0.1 degree in a 360-degree resolver shaft rotation.

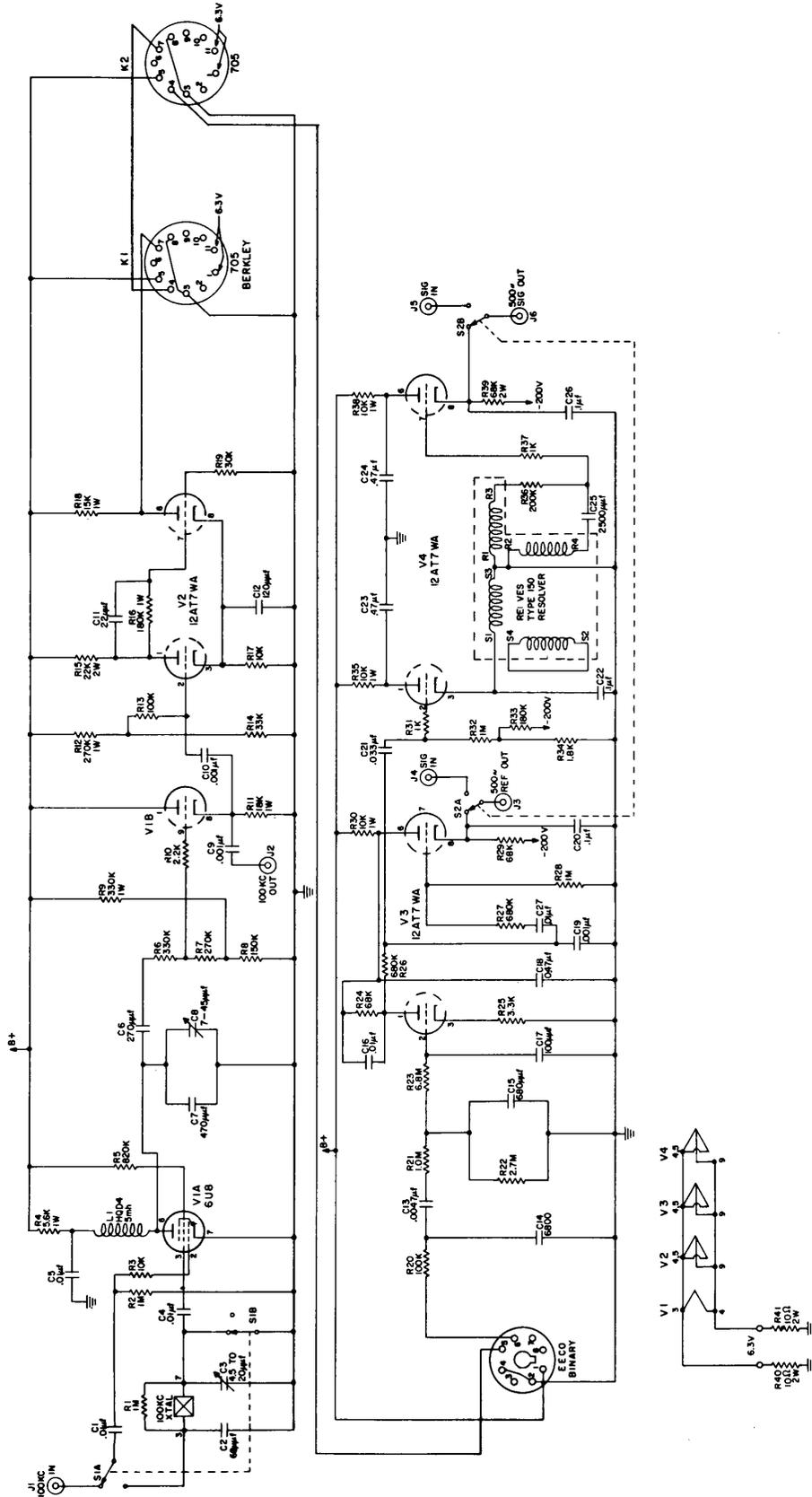


Fig. B1 - Test generator

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